

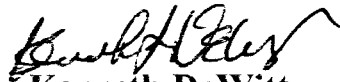
Final Technical Report

for

High Speed Operation and Testing of a Fault Tolerant Magnetic Bearing

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High Speed Operation and Testing of Fault Tolerant Magnetic Bearings

Background

The gas turbine industry has a continued interest in improving engine performance and reducing net operating and maintenance costs. These goals are being realized because of advancements in aeroelasticity, materials, and computational tools such as CFD and engine simulations. These advancements aid in increasing engine thrust-to-weight ratios, specific fuel consumption, pressure ratios, and overall reliability through engine operation at higher rotational speeds and higher temperatures with greater efficiency.

Rolling element bearings and squeeze film dampers are currently used to support gas turbine engine rotors. The bearings presently in operation are limited in temperature ($<500^{\circ}\text{F}$, 270°C) and speed ($\text{DN} < 2$ million), and require both cooling air and a lubrication system. Rolling element bearings in gas turbines are being pushed to their limits and new technologies must be found in order to take full advantage of other engine advancements.

Magnetic bearings are well suited to operate at elevated temperature and higher rotational speeds and are a promising solution to these problems. Magnetic bearing technology is being developed worldwide and is considered an enabling technology for new engine designs. Turbine and compressor spools can be designed with higher operating temperatures and significantly larger, stiffer, highly damped rotors, which spin at higher rotational speeds. Magnetic bearings will allow compressor, turbine, combustor, and nozzle advancements to reach their full performance potential.

Previous Work

The fault-tolerant magnetic bearing facility at NASA GRC has previously been used to develop control algorithms for individual coil failures within a magnetic bearing. It was successfully demonstrated that the bearing could suspend the shaft with as few as two coils, provided they were in the proper orientation to counter-act gravity. The facility has also been used to test unique hydrostatic backup bearings. These hydrostatic bearings are made from a unique, self-lubricating material that can function as a touchdown surface in the event of a magnetic bearing failure. These bearings were successfully demonstrated to 15,000 RPM in this facility.

Research Activities

The following describes the research activities undertaken to upgrade the fault-tolerant facility, continue testing high-speed fault-tolerant operation, and assist in the commission of the high temperature (1000°F) thrust magnetic bearing.

The fault-tolerant magnetic bearing test facility was upgraded to operate to 40,000 RPM. The necessary upgrades included new state-of-the art position sensors with high frequency modulation and new power edge filtering of amplifier outputs. A comparison study of the new sensors and the previous system was done as well as a noise assessment of the sensor-to-controller signals. Also a comparison study of power edge filtering for amplifier-to-actuator signals was done; this information is valuable for all position sensing and motor actuation applications. After these facility upgrades were completed, the rig is believed to have capabilities for 40,000 RPM operation, though this has yet to be demonstrated.

Other upgrades included verification and upgrading of safety shielding, and upgrading control algorithms. The rig will now also be used to demonstrate motoring capabilities and control algorithms are in the process of being created.

Recently, an extreme temperature thrust magnetic bearing was designed from the ground up. The thrust bearing was designed to fit within the existing high temperature facility. The retrofit began near the end of the summer, 04, and continues currently.

Mr. Clark, Mark Jansen, and Gerald Montague, together authored a NASA-TM entitled "An Overview of Magnetic Bearing Technology" for Gas Turbine Engines," containing a compilation of bearing data as it pertains to operation in the regime of the gas turbine engine and a presentation of how magnetic bearings can become a viable candidate for use in future engine technology.

Mr. Clark also aided the Flywheel group at NASA GRC on several projects, in particular, the design phase of the 3rd generation flywheel test rig. In his work, he conducted a number of thermal analyses on the proposed design and recommended changes to meet thermal limitations.



An Overview of Magnetic Bearing Technology for Gas Turbine Engines

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Introduction

The idea of the magnetic bearing and its use in exotic applications has been conceptualized for many years, over a century, in fact. Patented, passive systems using permanent magnets date back over 150 years. More recently, scientists of the 1930s began investigating active systems using electromagnets for high-speed ultracentrifuges (1). However, passive magnetic bearings are physically unstable and active systems only provide proper stiffness and damping through sophisticated controllers and algorithms. This is precisely why, until the last decade, magnetic bearings did not become a practical alternative to rolling element bearings. Today, magnetic bearing technology has become viable because of advances in micro-processing controllers that allow for confident and robust active control. Further advances in the following areas: rotor and stator materials and designs which maximize flux, minimize energy losses, and minimize stress limitations; wire materials and coatings for high temperature operation; high-speed micro processing for advanced controller designs and extremely robust capabilities; back-up bearing technology for providing a viable touchdown surface; and precision sensor technology, have put magnetic bearings on the forefront of advanced, lubrication free support systems. This paper will discuss a specific joint program for the advancement of gas turbine engines and how it implies the vitality of magnetic bearings, a brief comparison between magnetic bearings and other bearing technologies in both their advantages and limitations, and an examination of foreseeable solutions to historically perceived limitations to magnetic bearing.

Research Programs

Magnetic bearing research is a vital component for programs such as the Versatile Affordable Advanced Engine (VAATE) program. VAATE is a consortium of almost every major industrial player, multiple branches of the military, and NASA, making it the ubiquitous program of its kind, in other words, the "only game in town." This program hinges on a convolution of various advanced technologies to create an ultra-efficient, clean, intelligent, versatile, and durable gas turbine engine. The program's goals are aimed towards a yearly increase in capability/cost index, a measure of technological improvements over the operation and maintenance costs, with the long-term goal of a 1000 percent increase in the index by 2017.

VAATE sites specific advanced technologies as it focuses on three main areas of engine research: versatility, intelligent capabilities, and durability. The active magnetic bearing is the key enabling sub-technology for many of the advanced technologies of interest.

Magnetic bearings directly address the following topics of interest:

- Integrated health monitoring system
- Model based, non-linear, adaptive control system
- Integral starter generator
- Robust, damage tolerant design

In order to meet the challenges of advanced technologies, continued research in magnetic bearings is vital. Recent research, discussed later, has shown that technological improvements can transcend the classic shortcomings of magnetic bearings. With the rapid maturation of magnetic bearings, the next generation of turbine engine is quickly approaching.

Technological Overview

The active magnetic bearing is a rotor support that uses magnetic force to hold the rotor in place as opposed to the forces of a rolling element or air foil bearing. Like other bearing types, the magnetic bearing can be characterized in terms of stiffness, damping, and load capacity, thus the forces that apply these properties are somewhat analogous for each bearing. As shown in figure 1, a magnetic bearing consists of multiple electromagnetic coils attached to a ferromagnetic stator. The coils are arranged such that opposite poles are adjacent, maximizing magnetic flux through the rotor. A ferromagnetic, laminated rotor stack is attached to the shaft to provide the flux path and attractive magnetic forces while minimizing eddy current formation. Position sensors are fixed a certain distance from the shaft, on the order of thousandths of an inch. The voltage output from the position sensors and subsequent signal conditioning relays position information to the microprocessor controller, which uses this information to produce a command signal. The command signal is transferred to a proportional current through power amplifiers and output to the magnetic coils, providing an attractive magnetic force to the rotor. Typically, control algorithms treat the rotor support system as a mass/spring/damper interaction on two axes, usually vertical and horizontal. The controller will output signals proportional to the shaft's displacement from center.

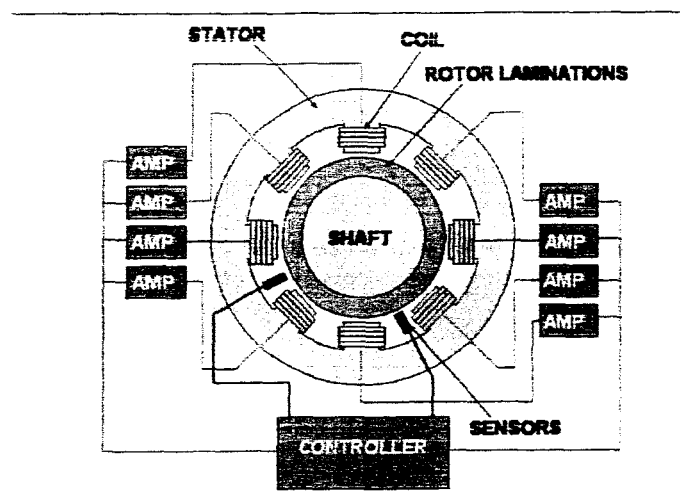


Figure 1.—Hetero-polar magnetic bearing.

Advantages and Limitations

Using a magnetic bearing for turbine engine applications results in three major technological advantages: oil-free operation with no air requirements, operation in extreme temperature environments, and active control. Proceeding from these advantages is a laundry list of desirable improvements to the turbine engine. They include reduced weight; no bearing contact, no wear, and less maintenance; operation in high altitudes; the subtraction of an oil, lube, and cooling system; bearing placement in the engine's hot sector; shorter, thicker and highly damped shafts; blade tip clearance control and stall suppression; fault tolerance; control of shaft imbalance; and dynamic stiffness and damping. The magnetic bearing also enables integral starter-generator (ISG) technology that could replace the bulk, complexity, and cooling/lubrication needs of a separate shaft/gearbox driven generator.

Table 1 presents a comparison of three bearing types in terms of specific "limiting factor" characteristics. Rolling element, air foil, and magnetic bearings each have viable applicability for gas turbine engines depending on the size, speed, and intelligent capabilities desired. Superior experimental capabilities were observed primarily by Dellacorte et al. (2,3) and Montague et al./Jansen et al. (4,5) for foil and magnetic bearings, respectively.

TABLE 1.—COMPARISON OF EXPERIMENTAL ACHIEVEMENTS
FOR VARIOUS BEARING TYPES

	Rolling Element	Foil Bearings	Magnetic Bearings
Max Operating Temp.	350–500 °F (180–260 °C)	1200 °F (650 °C) *Ref (2)	1000 °F (540 °C) *Ref (4)
Documented Operating Speed (DN) (Speed*ID)	Less than 2 million DN (RPM*mm)	2 million DN (2" dia.) *Ref (2) *theoretically limit is unknown	2.25 million DN (3" dia.) *Ref (5) *theoretically limit is unknown
Documented Load Capacity	Varies: wear, heating, lube breakdown Highest load capacity per square inch (~300 psi)	Proportional to rotation speed 0 to ~1000 lbs (4" dia.) max range for largest bearing size (~100 psi) *Ref (2,3)	For entire speed and temperature range 1000 lb/axis (116 psi) (3" dia.) *Ref (4,5)
Energy/Power Consumption	6–8 kW @12krpm 7–11 kW @ 17krpm (4.7" dia) *Ref (7)	No data	2.1 kW @ 1000 °F, all speeds *Ref (4,6)

Rolling element bearings are advantageous because they are well understood and offer significantly more load capacity per square inch of bearing sleeve surface area. Unfortunately, rolling element bearings have reached their technological limit in temperature and DN (speed in rpm x shaft thickness in mm) and have a relatively short lifetime at higher loads. In order for engines to run hotter and faster with long life times, they must eventually be redesigned around an air foil or magnetic bearing.

The different load capacity characteristics of foil and magnetic bearings offer applicability in separate engine regimes. Magnetic bearings are better suited for a large engine operating at high loads and relatively (when compared to a foil bearing) lower speed, the opposite is true for air foil bearings. Air foil bearings do not exhibit high load capacity at lower speeds and also, presently, have not been demonstrated at a size suitable for large engines. The tribological coating on the rotor used for smooth starts/stops and bearing rubs fails to adhere under the centrifugal loading of a high speed, large diameter

shaft. There is a similar limit for magnetic bearings due to the material strength of the rotor's ferromagnetic alloy, but the speed and diameter constraints are much higher.

Magnetic bearings offer several attractive features in addition to the task of supporting the shaft. It is possible to actively control blade tip clearance, avoiding seal rubs, and minimize the stall-mass flow for surge and rotating stall. Wang et al. (8) developed a controller design and Spakovszky et al. (9) demonstrated a 2.3 percent reduction in stall-mass flow in a high-speed compressor. The result is comparable to using unsteady air injection for the same purpose, but avoids the costly, heavy, and complex incorporation of the air injector system and also the penalty for recirculating air.

In current turbine engines, a shaft geared to one of the engine spools drives the power-takeoff assembly and alternator. This assembly requires lubrication and adds to weight and complexity. Magnetic bearings offer the invention of a starter-generator that is integral to the engine's main shaft. The Navy Magnetic Bearing System Integration Program demonstrated a magnetic bearing/ISG combination at 17 kRPM and is currently examining motor capabilities as well. In these respects, a magnetic bearing, unlike any passive system, brings multiple functionalities to the turbine engine design. In a sense, many intelligent systems "come free" with the installation of a magnetic bearing.

Solutions for Shortcomings

For many years, debate has swirled over the applicability of magnetic bearings for turbomachinery and turbine engines. Detractors such as Bently et al. (10) claim that the inadequacies of magnetic bearings are inherent to the technology, meaning the very principles on which the technology is based, i.e. material properties, electromagnetic properties, and rotor dynamics, show that magnetic bearings could never be applicable and robust for large-scale turbomachinery. In other words, magnetic bearings will never work regardless of technological improvements. Still, researchers continue to study, every year advancing towards superior milestones of speed, temperature, load capacity, fault tolerance, and materials research. Those that continue to achieve these milestones say that the disadvantages can be overcome with increased knowledge and superior engineering and design practices.

Kasarda (1) outlines an array of active magnetic bearing applications currently in use such as centrifugal compressors, turboexpanders, turbines, turbomolecular pumps, and machine tool spindles. Reference (1) describes these applications in detail, discussing the benefits of fitting these applications with active magnetic bearings and citing specific examples of standard industrial use. The bulk of commercial examples are not discussed in detail here, but one is worth mentioning. The NOVA natural gas pipeline commissioned a 10,444 kW centrifugal compressor in 1985 and over the next 15 years commissioned over 30 others. Alves and Alavi (11) discussed the reliability of these magnetic bearing compressors, claiming that the magnetic bearing systems surpassed that of conventional bearing systems while reporting an astounding 99.9 percent reliability. Magnetic bearing manufacturers discuss similar reliability numbers for other turbomachinery applications. Clearly, there are many examples of successful magnetic bearing application despite the apparent shortcomings of the technology.

There are three oft-sited disadvantages to current magnetic bearing technology, which Bently describes as fundamental: no viable back-up bearing technology and failure compensation, inadequate heat removal from the bearing, and a deficiency in load capacity, force compensation, and dynamic stiffness. Bently claims that these disadvantages presented themselves in the early 1980s and have yet to be effectively overcome, though industrial applications and recent research has shown otherwise.

Back-Up Bearings

Because of a significant gap requirement for back-up bearings, a high speed touchdown event due to total power loss could be catastrophic with heavy rotor bounce and uncontrolled vibration. Typical back-up bearing systems consist of a ball bearing with an inner race and rotor gap that is just inside the rotor/magnetic pole gap. During a power-loss event, ball bearings provide almost no stiffness or damping without a zero-clearance fit, thus a load-sharing back-up bearing would offer a better solution, allowing for a "limp home" mode of operation (1). Obvious choices for load sharing bearings would be hydrodynamic (foil) or hydrostatic bearings. Work at the NASA Glenn Research Center examined Graphalloy[®] hydrostatic bearings, qualifying them by load capacity, wear rates, temperature rise, and the ability to support a shaft through the entire speed range. Jansen et al. (5) demonstrated a combination magnetic bearing/hydrostatic bearing rotor support system at 30,000 rpm and 1000 °F.

Fault tolerance is another effort to prevent crash-down events. Aside from total power loss, capabilities to control a rotor with individual coil or amplifier failures have increased dramatically. Several research groups [12-15] have examined innovative approaches to fault tolerant control algorithms including flux coupling, which provides uncoupled and linearized control forces but may limit load capacity because of flux saturation, and flux isolation, which employs a redundant control axis.

Hardware consideration is also very important to fault tolerant systems. State-of-the-art microprocessors are now available that run fault tolerant algorithms on the order of microseconds, allowing for robust and intelligent controller designs. Choi and Provenza (16) demonstrated levitation and operation at 20,000 rpm with 6 of 8 coil failures in an open-loop experiment. A group at the University of Virginia has examined the use of current comparators for fault detection and closed-loop fault tolerance. Fortunately, both the control and power electronics can be scaled down to the microchip level, eliminating bulk and weight concerns for use in engines and flight systems. Ling, Le, and Lew (17) summarize the developmental effort of current commercial advanced electronic packaging for space applications that include chip-on-board (COB) technology, flip-chip (FC) interconnect technologies, and high-density interconnect (HDI) with microvia printed wiring board (PWB) technology. Several manufacturers (Xilinx, Inc., Northrup-Grumman) produce miniaturized controllers and miniaturized, space-rated power electronics that are tolerant of severe vibration, substantial temperature fluctuation and radiation degradation.

High Temperature

Another concern is the inability to remove heat generated by eddy current losses in the stator core and resistance heating in the electromagnetic coils. Significant advances in high strength ferromagnetic materials, such as Hyperco 50HS, and heat treatment processes have been made in the past few years. Improvements in manufacturing processes allow for thinner laminations and the further reduction of eddy current losses. Hyperco 50 is an iron-cobalt-vanadium soft magnetic alloy that has a high magnetic saturation and high maximum permeability while maintaining good mechanical properties. A new patent-pending C-core bearing technology (18) employs a modular stator design, specially coated silver wire, heat treated 0.014" thick laminations, and ceramic potting that show reduced resistance losses and no coil damage over hundreds of hours at elevated temperature and many thermal cycles (up to 1000 °F). The silver wire maintains a low resistance at elevated temperatures, reducing i^2R power losses in the coils. The patent-pending ceramic wire insulation maintains its dielectric integrity through many thermal cycles and long exposures to elevated temperatures, has good adhesion to silver without cracking or flaking under thermal expansion, and is pliable to allow for small radii turns. The ceramic potting that encapsulates each C-core withstands an operating temperature of 3000 °F. These high temperature coils also provide up to 1000 lb of force each, making them a candidate for turbine engine bearings.

Montague et al. (4) developed and demonstrated the first high load (1000 lb/axis), high temperature (1000 °F), and fault tolerant active magnetic bearing that achieved rotation speeds up to 30,000 rpm (5), spending over 32 hours at extreme temperature. Mekhiche, et al. (19) developed a magnetic bearing for operation at 1100 °F and 50,000 rpm, however, only room temperature results were reported. Data has shown that heat removal is a non-issue once the hardware can be tolerant of extreme temperatures.

High Loading Events and Dynamic Stiffness

Finally, there are the questions of high loading events such as high-g maneuvers, landings, and turbine blade loss, and a deficiency in dynamic stiffness. No bearing or squeeze film damper system exists that can handle a blade loss event (20), to this effect, magnetic bearings have no disadvantage. But, of the various damper technologies, the dynamic characteristics of the magnetic bearing make it the most adaptable for unplanned events. As for high-g maneuvers and landing events, total load capacity is the main factor. Though magnetic bearings and foil bearings alike are inferior to rolling element bearings in this regard, magnetic bearing load capacities have clearly increased beyond expectation (4,5,6,17,21). With further advances in high strength magnetic materials, load capacity will continue to increase. Recent work at NASA GRC demonstrated continuous operation of a magnetic bearing flywheel at 60,000 rpm. This is possible by maintaining a high level of controllability and stiffness throughout the entire bandwidth of operation. Advanced materials and controllers are available that permit greater dynamic stiffness.

Conclusion

Though magnetic bearing technology is far from young, it did not become practical for widespread application until fairly recently. High speed micro processing enables active magnetic bearing systems with stable control and dynamic stiffness and damping. The magnetic bearing is no longer an exotic technology, but finds applicability in an array of industries. One such application is the gas turbine engine. A large portion of government and industry partners attest to the value of magnetic bearings for gas turbine engines because of lubrication free operation with no air requirements, operation in extreme temperature environments, and active control for intelligent engines. Furthermore, the magnetic bearing enables a corresponding technology, the integral starter-generator, which subtracts the costly, gearbox driven starter and alternator. Recent research has demystified potential disadvantages, demonstrating high-speed, high-temperature, high-load, and fault tolerant operation. These milestones are met through advancements in magnetic materials, wire materials and potting techniques, electronic hardware, control algorithms, and high temperature sensor technology. Though still a number of years away, the aerospace industry will surely see a fully electromagnetic gas turbine engine.

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